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review OF RECENT DEVELOPMENTS

Mechanical Properties of Metals

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J. E. Campbell May 10, 1968

LOW-TEMPERATURE PROPERTIES

Additional data on the properties of alloys for cryogenic applications have been reported by General Dynamics/Convair.(1) The tensile-property data for these alloys as sheet (0.063 to 0.125-inch thick) are summarized in Table 1. The properties data of Alloy 718 and Ti-5Al-2.5Sn (ELI) at -423 F reconfirm earlier data for strength and ductility of these alloys at very low temperatures. The Ti-6Al-4V (ELI) alloy has lower ductility and notch toughness than the Ti-5Al-2.5Sn (ELI) alloy at -423 F. Of the three aluminum alloys in Table 1, the new alloy, X2021-T8E31, apparently has higher yield strength than the 2219-T81 and 7039-T64 alloys and exhibits good ductility and notch toughness at -423 F. The same report contains considerable data from tests on center-notch and single-edge-notch fracture-toughness specimens for these alloys at cryogenic temperatures. Because of the problems associated with obtaining plane-strain fracture-toughness data at very low temperatures, some of the data do not comply with the usual requirements for valid K_{Ic} data.

Tensile and fatigue data have been obtained on four condidate liquid-rocket alloys at 70 F, -320 F, and -423 F (or -452 F) in a recent program at the Lewis Research Center.(2) Results of the tensile tests are summarized in Table 2. The yield strengths, ultimate strengths, and notch strengths were higher for these alloys at the low temperatures than at room temperature, except for the notch-tensile strength for the cold-rolled Type 301 stainless steel. Data for fatigue-strength-to-density ratios versus fatigue life are plotted for each of the four alloys (at 70 F, -320 F, and -452 F) in Figure 1. When plotted in this way, the Ti-5Al-2.5Sn alloy rates higher than the others over certain portions of the fatigue-life range. The fatigue tests were made by axial-tension loading at a cyclic stress ratio R of 0.14.

Results of an extensive research program to develop an improved high-strength, high-toughness, and weldable aluminum alloy for cryogenic applications have been reported by Alcoa.(3) Nominal compositions of the two alloys that had the best properties are as follows:

X2021	X7007
6.3% Cu	6.5% Zn
0.15% Cd	1.8% Mg
0.05% Sn	0.20% Mn
0.30% Mn	0.12% Cr
0.18% Zr	0.12% Zr
0.10% V	0.10% Cu
0.06% Ti	0.04% Ti

Tensile properties for specimens from 0.125-inch-thick sheet for each of these alloys are presented in Table 3. The strengths of these alloys increase as the testing temperature is reduced to -452 F while the ductility and relative notch toughness (K_t=10) are not reduced for the X2021-T81 alloy at the low temperatures. Testing temperatures of -320 F and -452 F result in some reduction of the notch toughness of the X7007-T6E136 alloy. Resistance to stress corrosion of the X2021-T81 alloy is relatively good, and this alloy has good weldability. The X7007-T6E136 alloy has relatively good stress-corrosion resistance in the longitudinal and long-transverse directions, but is susceptible to stress-corrosion cracking in the short-transverse direction at stress levels as low as 25 percent of the yield strength. Weld tensile strengths are high for the X7007-T6E136 alloy and approach 60 ksi.

FRACTURE-TOUGHNESS TESTING

Even though the single-edge-notch specimen has not been adopted as a standard-type specimen for fracture-toughness testing, significant data have been reported by the Naval Research Laboratory for a number of alloys for which this type of specimen was used.(4) The data are summarized in Table 4. The intent of the program was to evaluate the effect of shallow side grooves on the K_{Ic} values obtained for single-edge-notch specimens. The side grooves tended to suppress the shear lip formation on fracturing and thereby aided in the detection of plane-strain fracture initiation (pop-in). The data in Table 4 represent K_{Ic} values for a number of materials that are used at high-strength levels. The specimens were 1-inch thick, 5-inches wide, and 13-inches long.

In a recent report from Boeing, information on fatigue-crack propagation, residual strength, and fracture toughness is presented for center-notch panels in sheet and plate thicknesses of 7079 aluminum alloy in the underaged, peak aged (T6), and overaged conditions.(5) The curves for the number of fatigue cycles for failure of 0.63-inch-thick panels based on the ratio for initial applied stress intensity/critical plane-strain stress intensity (K_{Ii}/K_{Ic}) are shown in Figure 2. This kind of information is applicable in estimating the fatigue life of cracked panels in service. The overaged panels had longer lives than comparable panels that were underaged or peak aged (T6). Fracture-toughness data on center-notch panels of 8, 12, and 36-inch widths are shown in Figure 3. For each panel width, the 0.50 and 0.63-inch-thick panels appeared to be thick enough to yield valid plane-strain fracture-toughness data for this alloy (36 to 40 ksi $\sqrt{in.}$ for longitudinal panels with the T6 aging treatment).

TABLE 1. AVERAGE TENSILE PROPERTIES AT CRYOGENIC TEMPERATURES OF ALLOYS AS SHEET (1)

Alloy	Testing Temperature, F	Specimen Direction	Yield Strength, 0.2% Offset, ksi	Tensile Strength, ksi	Elong. in 2 inches, percent	Elastic Modulus, psi x10^6	Notch/Unnotch Strength Ratio (a)
Alloy 718 (Aged) (Ni base)	75	L	161	192	24.6	31.0	1.12
		T	164	194	22.8	31.0	1.10
	-110	L	173	213	29.0	31.0	1.08
		T	171	209	29.0	30.2	1.08
	-320	L	194	246	22.4	31.8	1.03
		T	192	245	21.0	-	1.02
	-423	L	208	275	22.5	29.9	0.97
		T	207	267	18.3	-	0.97
Alloy 718 (Annealed)	-423	L	91.4	178	61.0	-	0.92
		T	89.9	174	55.4	-	0.90
X2021-T8E31 Al Alloy	75	L	54.6	67.0	9.8	11.6	0.97
		T	54.5	67.5	9.5	11.1	0.96
	-110	L	58.2	72.1	11.0	10.2	0.97
		T	58.1	71.9	11.0	11.2	0.97
	-320	L	65.8	85.2	12.5	10.4	0.95
		T	64.7	84.5	13.0	10.9	0.93
	-423	L	73.8	101	14.0	12.0	0.92
		T	70.3	99.4	15.0	12.0	0.93
2219-T81 Al Alloy	-423	L	67.4	94.6	15.9	11.9	0.91
		T	67.2	100	15.5	13.2	0.85
7039-T64 Al Alloy	-423	L	62.2	89.6	21.0	10.1	0.91
		T	64.4	93.4	17.0	11.0	0.88
Ti-5Al-2.5Sn (ELI) Annealed	-423	L	213	235	13.5	19.4	0.97
		T	210	233	17.6	19.0	0.91
Ti-6Al-4V (ELI) Annealed	-423	L	245	256	3.5	20.0	0.77
		T	249	254	2.0	19.6	0.75

(a) The notched specimens had $K_t = 6.3$.

TABLE 2. AVERAGE TENSILE PROPERTIES AT CRYOGENIC TEMPERATURES OF FOUR ALLOYS AS SHEET(2)

Alloy	Testing Temperature, F	Yield Strength, 0.2% Offset, ksi	Ultimate Strength, ksi	Modulus of Elasticity, psi x10^6	Notch Strength,(d) ksi
2024-T6 Aluminum	70	65.6	71.1	10.9	56.4
	-320	77.4	86.3	11.5	56.1
	-423	84.1	102	12.0	60.6
Alloy 718 (Ni base)(a)	70	153	184	30.7	183
	-320	182	241	32.4	214
	-423	195	257	32.7	229
Ti-5Al-2.5Sn Annealed(b)	70	105	111	16.5	126
	-320	176	182	17.8	181
	-423	210	229	18.4	140
AISI 301 Stainless Steel(c)	70	218	234	25.3	220
	-320	256	334	26.7	219
	-423	300	337	28.0	184

(a) Solution annealed at 1950 F 1 hr., air cooled, aged at 1350 F 9 hr, furnace cooled to 1200 F, held at 1200 F 9 hr., air cooled.
(b) Mill annealed at 1325 F 4 hr., furnace cooled.
(c) Cold rolled 60 percent.
(d) Notch specimens had K_t>17.

Additional data on the fracture toughness of aluminum alloys are presented in the next section.

Two new testing techniques have been developed at the Naval Research Laboratory for evaluating the toughness of welds in quenched-and-tempered steel plate.[6] Schematic presentations of these techniques are shown in Figures 4 and 5. Charpy data, drop-weight nil-ductility temperature (NDT) data, and drop-weight tear-test data are included for the quenched-and-tempered steels. Results of the nil-ductility temperature tests indicated that there was a substantial rise in the NDT when the notches were located at the fusion lines of welds of "lean-analysis" quenched-and-tempered steels. In performing the drop-weight bulge tests, a 6-ton weight was dropped from a height of 8 feet onto a soft aluminum tup located at the center of the test specimen. Specimens were cooled to a temperature of 30 F. Each specimen was subjected to repeated blows until visible cracking had occurred beyond the brittle crack starter. The number of blows or the accumulated energy to cause crack formation, the length of the fracture, and the amount of deformation required to produce fracturing are indications of the relative toughness of the specimen. The delta-specimen tests also were conducted at 30 F. Each specimen was continuously loaded until the center of the specimen had deflected to 3 inches below the tops of the three support blocks. The extent and location of cracking was observed. The lean steels developed substantially longer cracks than the specimens of more highly alloyed steel. These tests on welded specimens of quenched-and-tempered steels are more indicative of relative toughness than tests on the parent metal which often does not have a well-defined transition temperature.

MECHANICAL PROPERTIES OF ALUMINUM ALLOYS

Tensile, compressive, shear, bearing, fracture toughness, and axial-load fatigue properties of 143 lots of 2014, 2024, 6061, 7075, 7079, and 7178 aluminum-alloy extrusions have been reported by Alcoa.[7] The range of thicknesses was 0.050 to 6.500 inch, and the alloys represented several different tempers. The objective of the program was to obtain data for design mechanical properties tables for use in MIL-HDBK-5. Values for tensile and compressive elastic moduli are as follows:

Alloy or Series	Thickness, inches	Elastic Modulus, psi: Tensile	Elastic Modulus, psi: Compressive
2000	All	10,800,000	11,000,000
6061	$\leq$ 0.499	9,700,000	9,900,000
6061	$\geq$ 3.000	10,300,000	10,600,000
7000	All	10,400,000	10,700,000

Computed design mechanical properties for 7075-T651X alloy extrusions are shown in Table 5 in the usual MIL-HDBK-5 format. The values in parentheses are differences from the corresponding properties in the last revision of the Handbook. Similar tables are presented for the other alloys evaluated in the program. Average K_{Ic} data representing fracture toughness of the above alloys (except 6061) as determined by the 5 percent secant offset method are shown in Table 6.

Since the aluminum alloys developed in the program and discussed in Reference 3 possess a desirable combination of properties, further evaluations were conducted at Alcoa to obtain the tensile, compressive, shear, bearing, bend, and fatigue properties as well as data on hardness, tear resistance, and fracture toughness.[8] For these studies, the alloys X2021-T81 and X7007-T6E136 were produced in

TABLE 3. TENSILE PROPERTIES OF NEW ALUMINUM ALLOYS AT CRYOGENIC TEMPERATURES(3)

Alloy	Thickness, inches	Testing Temperature, F	Direction	Yield Strength, 0.2% Offset, ksi	Tensile Strength, ksi	Elongation in 2 inches, percent	Notch Strength Ratio (a)
X2021-T81	0.125	RT	L	63.4	72.8	10.2	0.85
			T	62.4	73.4	9.5	0.78
		-112	L	69.3	79.1	10.0	0.91
			T	65.8	79.6	9.5	0.90
		-320	L	75.7	90.8	10.8	0.80
			T	73.5	92.2	10.0	0.77
		-452	L	82.8	97.0	9.0	0.91
			T	82.0	101	9.8	0.84
X7007-T6E136	0.125	RT	L	68.5	73.7	10.8	1.05
			T	65.6	70.8	12.0	1.08
		-112	L	76.4	83.0	9.5	1.00
			T	72.6	79.6	11.0	1.03
		-320	L	84.5	99.0	11.5	0.79
			T	81.2	93.0	12.5	0.79
		-452	L	83.8	94.9	8.5	0.88
			T	82.2	95.2	10.2	0.81

(a) Notch strength/unnotch strength ratio where notched specimens had K_t = 10.

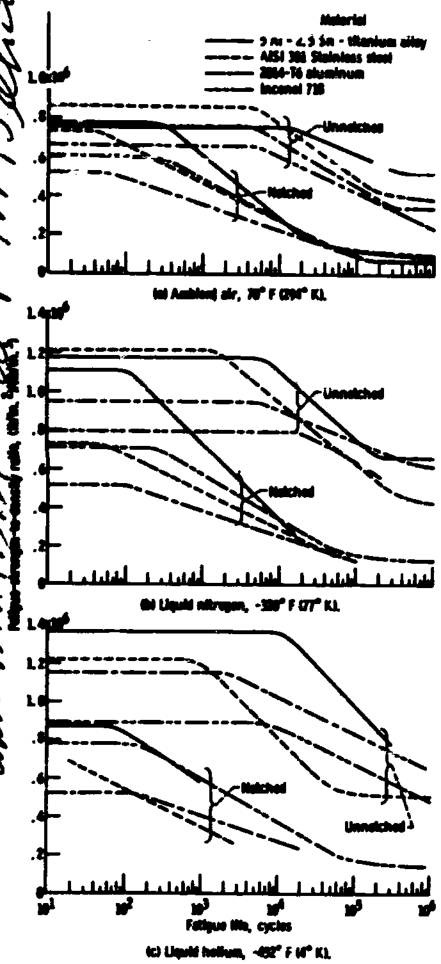

FIGURE 1. COMPARISON OF FATIGUE-STRENGTH-TO-DENSITY RATIOS AT 70 F, -320 F, and -452 F(2)

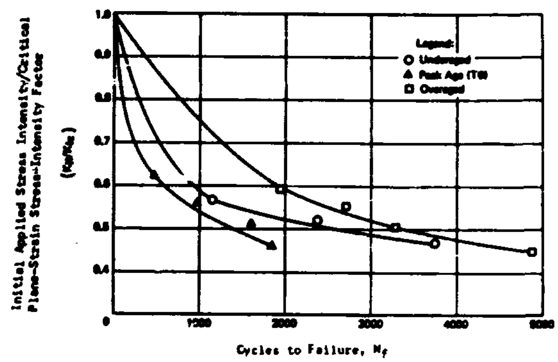

FIGURE 2. COMPARISON OF K_{Ii}/K_{Ic} VERSUS FATIGUE CYCLES TO FAILURE FOR 0.63-INCH-THICK 7079 UNDER-AGED, PEAK-AGE (T6), AND OVERAGED MATERIALS(5)

sheet and plate forms. Tensile properties of these alloys are presented in Table 3. Average values for elastic modulus are as follows:

Alloy	Direction	Tensile Modulus, psi	Compressive Modulus, psi
X2021-T81	L	10,600,000	10,900,000
	T	10,800,000	11,000,000
X7007-T6E136	L	10,400,000	10,600,000
	T	10,400,000	10,700,000

Compressive yield strengths are equal to or greater than the transverse tensile yield strengths. Longitudinal and transverse shear strengths are approximately 60 percent of the transverse tensile strength. The axial-stress fatigue limits at 5 x 10^8 cycles (R = 0.0) for unnotched specimens are as follows:

Alloy	Fatigue Limit, ksi Sheet	Plate
X2021-T81	27	26
X7007-T6E136	27	33

Typical values for fracture toughness of these alloys are as follows:

Alloy	Direction	K_{Ic} ksi $\sqrt{in.}$
X2021-T81	L	29
	T	23
X7007-T6E136	L	45
	T	37.5

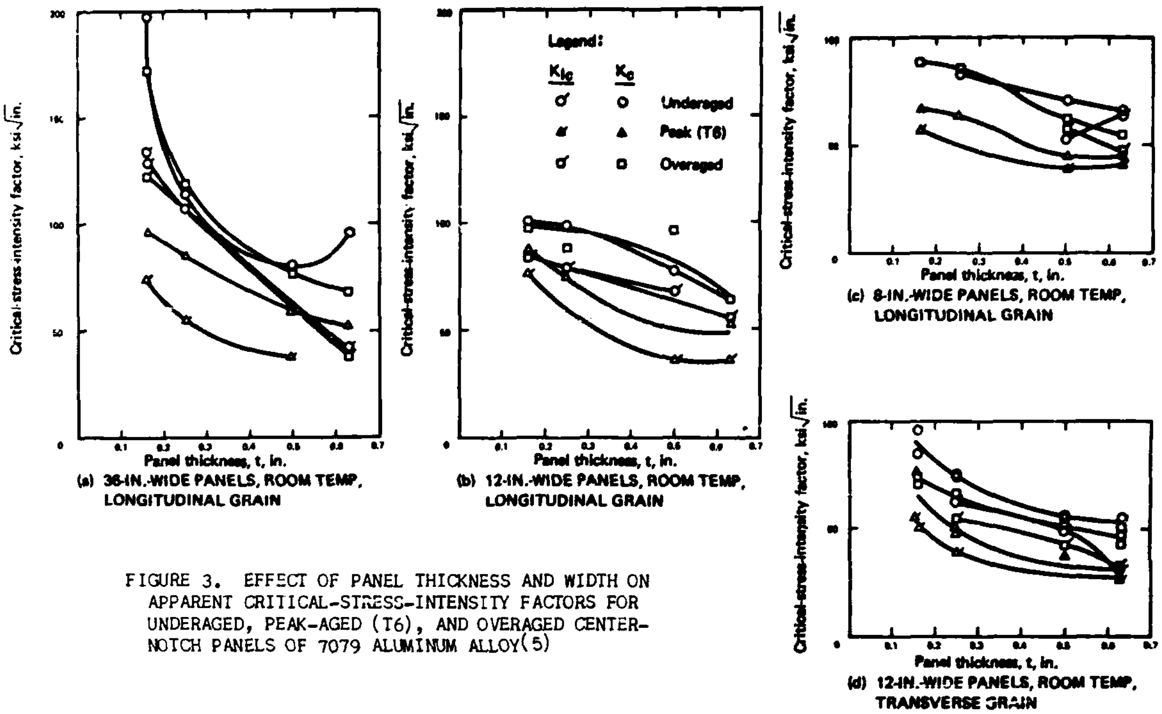

FIGURE 3. EFFECT OF PANEL THICKNESS AND WIDTH ON APPARENT CRITICAL-STRESS-INTENSITY FACTORS FOR UNDERAGED, PEAK-AGED (T6), AND OVERAGED CENTER-NOTCH PANELS OF 7079 ALUMINUM ALLOY[5]

TABLE 4. FRACTURE TOUGHNESS DATA OBTAINED USING SINGLE-EDGE-NOTCH SPECIMENS 1-INCH THICK[4]

Alloy	Fracture Direction	Yield Strength, ksi	Tensile Strength, ksi	Charpy V Energy at 32 F, ft lb	Average K_{Ic} Values, ksi $\sqrt{in.}$: No side Grooves	Average K_{Ic} Values, ksi $\sqrt{in.}$: With side Grooves
Titanium Alloys						
Ti-6Al-4V(a)	RW(g)	132	150	25	109	106
Ti-6.5Al-5Zr-1V (As received)	WR(h)	124	131	17	91	99
Ti-6Al-4Zr-2Mo (b)	WR	132	147	23	99	94
Ti-6Al-4V-2Sn (As received)	RW	114	124	-	[illegible]	95
Ti-6Al-4V-2Sn(c)	RW	130	141	24	79	90
Ti-6Al-4Zr-2Sn-0.5Mo-0.5V(d)	RW	118	131	18	121	118
Ti-6Al-4Zr-2Sn-0.5Mo-0.5V(e)	RW	119	130	30	110	110
Ti-6Al-4Zr-2Sn-0.5Mo-0.5V(f)	RW	121	129	27	131	124
Aluminum Alloys						
2219-T851	WR	58.4	74.3	5	37	33
7075-T6	RW	64.7	75.4	-	33	32
7075-T7351	RW	63.9	75.4	6	33	30
7075-T7351	WR	65.6	75.5	4	27	23
Steels						
AISI 4140 (NRL heat treatment)	WR	177	195	14	89	87
9Ni-4Co-0.25C (As received)	WR	176	187	40	165	163
9Ni-4Co-0.[illegible] heat treat)	WR	186	198	36	156	152
9Ni-4Co-[illegible] (As received)	WR	180	191	42	166	159
12Ni (NRL heat treatment)	WR	176	180	38	143	135
12Ni (NRL heat treatment)	WR	178	182	40	136	134
12Ni (As received)	WR	177	183	42	196	205
12Ni (As received)	WR	177	183	47	201	212

(a) 17[illegible] F 1 hr, WQ, aged 900 F 2 hr.
(b) 1800 F 1 hr, WQ, aged 1000 F 2 hr.
(c) 1775 F 1 hr, WQ, aged 1000 F 2 hr.
(d) 1800 F 1 hr, WQ, aged 1100 F 2 hr.
(e) 1750 F 1 hr, WQ, aged 1100 F 2 hr.
(f) 1825 F 1 hr, WQ, aged 900 F 4 hr.
(g) RW = edge notch on longitudinal specimen.
(h) WR = edge notch on transverse specimen.

TABLE 6. FRACTURE TOUGHNESS OF ALUMINUM ALLOYS[7]

Alloy and Temper	Fracture Toughness, K_{Ic}, ksi $\sqrt{in.}$: Longitudinal	Transverse
2014-T6510	30.1	25.4
2014-T62	28.6	28.0
2024-T851X	29.0	18.2
7075-T6510	28.0	23.6
7075-T62	—	23.8
7075-T73510	34.2	26.3
7079-T6510	30.9	29.2
7079-T62	35.8	—
7178-T6510	21.9	21.0
7178-T62	23.3	22.6

FATIGUE TESTING IN VACUUM

Current results from a program at Martin-Marietta for evaluating the effects of a vacuum environment on the fatigue properties of 1100 aluminum, 7075-T6 aluminum alloy, Ti-6Al-4V alloy, and Armco iron have been reviewed in a recent report.[9] The fatigue data were obtained on constant-stress reverse-bending tests for various combinations of stress, frequency, temperature, and air pressure. Typical curves for number of cyles to failure at different air-pressure levels are shown in Figure 6.

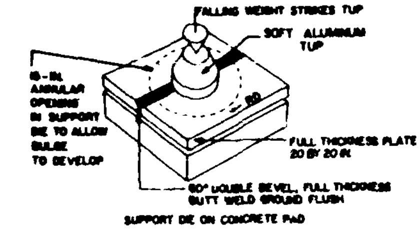

FIGURE 4. DROP-WEIGHT BULGE TEST[6]

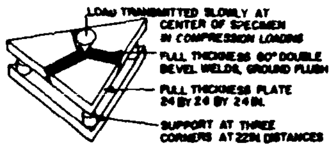

FIGURE 5. DELTA-SPECIMEN TEST [6]

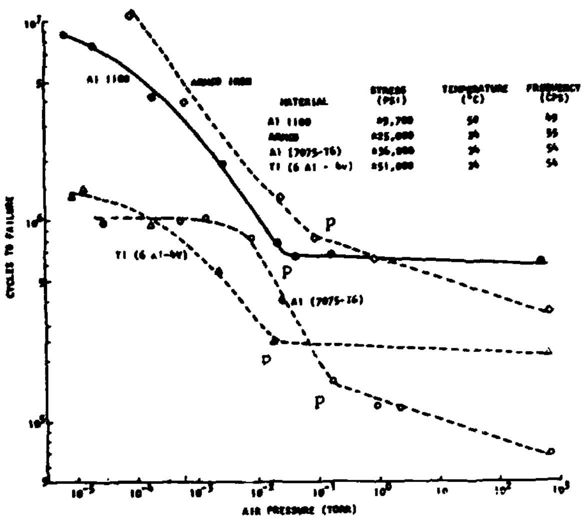

FIGURE 6. NUMBER OF CYCLES TO FAILURE AS A FUNCTION OF AIR PRESSURE FOR SPECIMENS OF 1100 ALUMINUM, 7075-T6 ALUMINUM ALLOY, Ti-6Al-4V ALLOY, AND ARMCO IRON[9]

The shapes of the curves suggest that three different ranges exist depending on the pressure. The points P on the curves represent threshold pressures for each material and indicate the transition from a weak-vacuum effect to a strong-vacuum effect on the fatigue properties. At somewhat lower pressures, there is a third range in which variations in pressure have less effect on the fatigue life. For 1100 aluminum alloy, increasing the frequency of stressing at 3 x 10^{-5} torr decreases the fatigue life while the fatigue life at atmospheric pressure was independent of the frequency from 33 to 95 cps. At elevated temperatures, the effect of vacuum on the fatigue life is diminished (for 1100 aluminum). For S-N curves at normal temperatures, decreasing the air pressure tends to displace the curves to the right for unnotched and notched specimens. In analyzing crack-nucleation characteristics of the above alloys, the author noted that the first microcracks appeared in specimens of 1100 and 7075-T6 aluminum at practically the same number of cycles under both vacuum and atmospheric pressure conditions for the respective alloys. For specimens of the Ti-6Al-4V alloy, however, microcrack formation was delayed by the vacuum environment. In determining the effect of the vacuum environment on crack propagation, crack propagation was observed to be slower in aluminum alloy specimens when exposed to the vacuum than when exposed to normal air pressure. Residual strengths of specimens precracked in a vacuum were higher than for comparable specimens precracked in air. All of these factors were considered in discussing a proposed mechanism to explain these conditions. The author concluded that the effects of vacuum on the fatigue properties of metals are probably the result of "vacuum-induced mechanical changes in the surface layer of a deformed specimen".

Effects of a vacuum environment on the fatigue properties of aluminum alloys also have been studied at the Naval Research Laboratory.[10,11] Of particular interest is the data for crack growth rates in specimens of 2024-T3 alloy in air and at a pressure of 2 to 3 x 10^{-6} torr as a function of the stress intensity amplitude, ΔK_I. For these specimens the crack growth rates in air were three times the crack growth rates in the vacuum environment for the same ΔK_I. Effects of the environment and other variables are illustrated in stereo macrographs and electron fractographs. Discussions of theories that have been proposed to explain the effects of a vacuum environment on the fatigue properties indicate that there is no agreement among investigators regarding the mechanisms.

SELECTED LIST OF NEW PROGRAMS

Fatigue. Contract No. F33615-67-C1547, Mechanisms of Fatigue in High Strength Materials, Midwest Research Institute.

Contract F41-608-67-A-6604, Evaluation of Fatigue Strengths of Compressor Blades and Vanes, Southwest Research Institute.

Contract NAS 3-10610-001, Low Cycle Fatigue Plastic Strain Range vs. Number of Cycles to Failure for Tantalum, General Electric Company, Flight Propulsion Division.

Contract Nonr - 4433 (00), Research on Material Failure Mechanism, SKF Industries, Inc.

Impulsive Loading. Contract F33615-68-C1138, The Ballistic Behavior of Materials and Response of Materials to Impulsive Loading, University of Dayton Research Institute.

Creep. Contract NAS 3-9439, Long-Time Creep Data on Refractory Alloys, TRW, Incorporated.

Environmental Effects. Contract Nonr-3363 (00)-(FBM), Behavior of Materials and Structures Under Certain Service Simulated Environments, Southwest Research Institute.

Steels for Motor Cases. Contract AF33(615)-66-03048, Process Evaluation for Large Solid Motor Cases Using HP9-4 Alloy, United Aircraft Corporation, United Technology Center Division.

TABLE 5. COMPUTED DESIGN MECHANICAL PROPERTIES OF 7075-T651X ALUMINUM ALLOY EXTRUSIONS(7)

Alloy	7075											
Form	Extrusions											
Condition	T6510 and T6511											
Cross-Sectional Area, in.^{2}	≤20										≤20	
Thickness, in.	≤0.249		0.250-0.499		0.500-0.749		0.750-1.499		1.500-2.999		3.000-4.499	
Basis	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:												
F_{tu}, ksi L	78	82	81	85	81	85	81	85	81	85	81	84
LT	76	80(+2)	78(+1)	81(+2)	76(+3)	80(+5)	74(+2)	78(+4)	70(+4)	74(+6)	67(+1)	70(+2)
F_{ty}, ksi L	70	74	73	77	72	76	72	76	72	76	71	73
LT	66(+2)	70(+3)	68(+2)	72(+4)	66(+3)	70(+4)	65(+3)	68(+4)	61(+4)	65(+5)	56	58
F_{cy}, ksi L	70(-1)	74(-1)	73(-1)	77(-1)	72	76	72(+1)	76(+1)	72(+2)	76(+3)	71(+5)	74(+5)
LT	72(+1)	76(+1)	74	78	72(-1)	76(-1)	71(-1)	74(-1)	67(-2)	71(-1)	61(-4)	64(-4)
F_{su}, ksi	42(-1)	44(-1)	43(-2)	45(-2)	43(-2)	45(-2)	42(-3)	44(-3)	41(-4)	43(-4)	40(-5)	41(-5)
F_{bru}, ksi e/D=1.5	112(+11)	118(+11)	117(+20)	122(+20)	117(+20)	122(+20)	116(+19)	122(+20)	115(+18)	120(+18)	109(+12)	113(+12)
e/D=2.0	141(+16)	148(+17)	146(+16)	153(+17)	146(+16)	153(+17)	145(+15)	152(+16)	144(+14)	151(+15)	142(+20)	147(+21)
F_{bry}, ksi e/D=1.5	94(+3)	99(+3)	97(+17)	103(+18)	96(+17)	101(+17)	95(+16)	100(+16)	93(+14)	98(+14)	89(+11)	92(+11)
e/D=2.0	110(+12)	117(+13)	115(+13)	121(+13)	113(+12)	119(+13)	112(+11)	118(+12)	110(+9)	116(+10)	105(+13)	110(+14)
e, percent: L	7	8	7	8	7	8	7	8	7	8	7	8
LT	5	—	5	—	4	—	3	—	1	—	1	—
E, 10^6 psi	10.4(+0.1)											
E_c, 10^6 psi	10.7(+0.2)											
G, 10^6 psi	4.0(+0.1)											

NOTE: Numbers in parenthesis are differences from values in MIL-HDBK-5, November 1967.

Data for 4.500-5.000 thicknesses omitted in this table.

REFERENCES

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